Shelf and Slope Sediment Transport in STRATAFORM

David A. Cacchione
Woods Hole Group
1167 Oddstad Drive
Redwood City, CA 94063
telephone: 650-298-0520 fax: 650-298-0523 e-mail: dcacchione@whgrp.com

Award Number: N0001499C0002

LONG-TERM GOALS

The overall long-term goal of STRATAFORM is to advance our understanding of the development and modification of stratigraphic sequences on continental terraces (shelves and slopes). An essential part of this understanding comes from investigations of modern sedimentary processes in these critical regions of the oceans. These investigations include modeling and direct measurements of the response of bottom and suspended sediment to oceanic forcing. In this project our specific long-term goal is to understand the effects that bottom stresses caused by physical oceanographic forcing have on shelf and slope sedimentation. This work is accomplished through modeling, and through analyses of available field measurements of waves, currents, suspended sediment concentrations, and bottom sediment distributions.

In this specific project we focus on understanding sediment dynamics in the two STRATAFORM study areas on the shelf and slope: (1) off the Eel River, California; and (2) off central New Jersey. Our research efforts are largely aimed at two processes: (1) the role of internal waves and tides in shaping the sediment cover of the upper continental slope; and (2) sediment resuspension and transport caused by bottom stresses associated with surface waves, tides, and quasi-steady currents.

OBJECTIVES

- Evaluate the role of internal waves and tides in transporting sediment on the continental slope in the STRATAFORM study regions.

- Investigate variability in the magnitude and directions of bottom stresses caused by currents and surface waves in the STRATAFORM field area off northern California.

- Estimate time-dependent sediment transport at specific shelf sites in collaboration with other investigators.

- Examine intense sediment transport events using bottom-boundary layer measurements to determine the significance of thin, near-bed, high concentration layers (e.g., fluid mud) for transport processes (in collaboration with others).

APPROACH

The internal wave work is being done in close collaboration with other STRATAFORM investigators: Dr. Lincoln Pratson (Duke University), Dr. Andrea Ogston and Dr. Richard Sternberg (U. of Washington), and Dr. Charles Nittrouer and his students (U. of Washington). Dr. Cacchione has also collaborated with Dr. Erica McPhee, recent Ph.D. at U. of Washington, on the role of internal waves in causing oceanic mixing and nepheloid layer generation (McPhee and Cacchione, 1998).

The effects of internal waves and tides on transport of bottom and suspended sediment are poorly understood. We have approached this problem both theoretically and using new data collected during the STRATAFORM experiments.

We gathered recent and historical CTD data to estimate vertical density profiles (and Brunt Vaisala frequencies, N) in the Eel River and New Jersey offshore regions. These density profiles were then used to compute the slope (relative to horizontal) of characteristics c for the internal tides and other internal waves.

$$c = \left(\frac{\omega^2 - f^2}{N^2 - \omega^2} \right)^{1/2} \tag{1}$$

ω is internal wave frequency (ω = 0.083 cph for the M2 internal tide). $f = 2\Omega \sin\phi$ is the Coriolis or inertial frequency with Ω the rotation frequency of earth (1 cyc/24 hours) and ϕ latitude in degrees. In the STRATAFORM area off the Eel River, $\phi = 41^{o}$, and f = 0.055 hr^{-1} (or inertial period = 18.3 hr). The Brunt Vaisala frequency N in s^{-1} is given by:

$$N = \left(\frac{g}{\rho} \frac{\partial \rho}{\partial z} \right)^{1/2} \tag{2}$$

g is gravitional acceleration; r is density; and z is depth (positive downward).

By comparing c with bottom gradients γ in the study area, we identified areas where internal tides and other internal waves would likely have maximum bottom shear along the seabed (i.e., where c = γ; Cacchione and Drake, 1986). We also used the long-term measurements of temperature and currents obtained at the upper slope mooring site (over 4 years of continuous data) in 450 m water depth to examine the internal wave dynamics.

A secondary part of this project has been to analyze with Dr. Ogston and Dr. Sternberg long-term sediment transport rates and mechanisms in the study region (Ogston, et al., 2000). We have collaborated on evaluating the role of fluid mud generation and transport on the overall transport scheme for the Eel River shelf. Instrumented bottom tripods that were deployed at many sites on the Eel River shelf during the five-year field program of STRATAFORM have been used in this analysis. This work has produced estimates of sediment flux and bottom stresses over long time periods at various shelf locations.

WORK COMPLETED

- We have presented our results dealing with the effects on sediment movement by internal tides and other internal waves at several professional society meetings and other symposia (Cacchione, et al, 1998, 1999, 2000). We have collected the historical and recent CTD data and computed vertical profiles of density and Brunt Vaisala frequency for the STRATAFORM regions, and calculated characteristic gradients. We have also computed and displayed (using GIS) bathymetric gradients for both STRATAFORM study areas.

- We have completed a draft manuscript that presents our results on sediment effects caused by internal tides on the continental slope. This paper will be submitted for publication.

- In collaboration with other STRATAFORM investigators we have completed and submitted a manuscript on sediment transport in dense, thin bottom layers on the Eel River shelf (Ogston, et al, 2000).

RESULTS

Internal tides and other internal waves have an important effect on sediment movement and distributions not only in the STRATAFORM study areas off northern California and New Jersey, but also on other oceanic slopes. Our focus has been on continental slopes in regions where the bottom gradients appear to be similar to the slopes of the internal M2 tidal characteristics. We have concluded that internal semi-diurnal tides play a major role in shaping continental slopes by inhibiting deposition of fine sediment over long time periods, and less frequently by eroding the bed. This important process had been described conceptually by Cacchione and Wunsch (1974) and Cacchione and Southard (1974), but this recent analysis provides strong evidence for its significance on a global scale.

Using available CTD and detailed bathymetric data we calculated the slopes of internal wave characteristics and gradients of the seafloor in the STRATAFORM study areas. The results indicated that over large sections of both regions internal M2 tides were critical or near-critical (within 10% of critical). Critical is defined as equivalence of the two gradients (i.e., $c = \gamma$). An interesting result of this analysis was that the zones of criticality vary significantly in different seasons off New Jersey, whereas little seasonal variability is found off northern California. This difference was apparently controlled by the nature of the density profiles. Off New Jersey the historical temperature and salinity profiles between about 100 and 1000 m changed significantly from winter to summer; whereas, off northern California the variability in the historical profiles was much less.

We also developed an expression for bottom shear velocity u_{*b} under shoaling critical internal waves, and used this expression to assess the likelihood that internal M2 tides inhibit deposition of fine sediment on continental slopes. The expression used recent laboratory results for energy dissipation in the bottom boundary layer under shoaling critical internal waves (Ivey, et al., 2000). We found that typical values of u_{*b} for near-critical internal tides were close to 1 cm/s, and were large enough to retard settling of fine sediment onto continental slopes. This finding implies that as slope surfaces prograde seaward and bottom gradients decrease, they would become near-critical (in relation to c for internal tides). Because of the increased bottom shear at near-critical conditions, sedimentation from particle settling would be reduced. The slope surfaces will essentially adjust to equilibrium profiles that have gradients approximately equal to c. The worldwide average slope of continental slopes is about 2.5^{o}, approximately equal to the average value of c for internal M2 tides.

These results suggest that turbulent bottom shear caused by the interaction of the internal M2 tides with the seabed is an effective and important mechanism for controlling sedimentation on the continental slope. These shears might control the rate and declivity at which continental slopes prograde throughout long time periods, effectively maintaining an equilibrium bottom gradient (in balance with the energy and turbulent shear associated with the internal semi-diurnal tide).

IMPACT/APPLICATIONS

If our analysis bears up under closer scrutiny and continuing analysis, we will have uncovered an important geological process that has not received wide application in morphological and sedimentological models of the floor of continental margins. The slow deposition of fine particulate matter onto the surface of the continental slope might be in large part controlled by the nature of the turbulent shears associated with this process. During periods when the internal tidal motions are highest, which varies considerably over the year as determined by our analysis of the STRATAFORM current and temperature data off California, turbulent shears may reach values large enough to prevent deposition of fine sediment (clay and silt sized particles), and may even cause local resuspension of bottom sediment.

This work has applications for modeling of formation of sediment units on continental slopes. It may also have implications for sedimentation on certain continental shelves where turbulent shears from surface waves and other currents are relatively low (as compared with internal wave effects). Also, in a related project we have found that internal tidal currents and shears are large along the island slopes of Hawaii (Cacchione, et al., 2000). This result suggest that internal waves interacting with slopes along islands, seamounts, and guyots might also be important for sediment processes in these regions. For example, Cacchione, et al. (1988) proposed that sediment ripples on top of Horizon Guyot in about 1500 m water depth were formed and actively moved by internal tidal currents.

TRANSITIONS

These simple model that predicts the condition for maximum bottom shear (including the formulation for u_{*b}) for internal M2 tides over the continental slope will be incorporated into an omnibus model for shelf and slope sedimentation processes being coordinated by Dr. James Syvitski and others under ONR support. This model development and incorporation into the larger sedimentation models will occur during FY02.

RELATED PROJECTS

This project is closely related to those STRATAFORM projects investigating morphology and surface sedimentation on the upper slopes and outer continental shelves. The work on internal tides and sediment movement is related to projects led L. Pratson (Duke University), R. Sternberg, C. Nittrouer, and A. Ogston (all three at University of Washington), J. Syvitski (INSTAR, University of Colorado), and G. Parker (University of Minnesota).

The work on sediment resuspension and transport by waves, currents and other processes that includes analysis of bottom tripod data is directly undertaken in collaboration with P. Wiberg (University of Virginia), L.D. Wright and C. Friedrichs (VIMS), and R. Sternberg and A. Ogston (U. of Washington).

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